

Radar Autofocus Algorithm Incorporating Terrain Knowledge for Correction of Mars Ionospheric Distortion in MARSIS Observations

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May 11, 2017



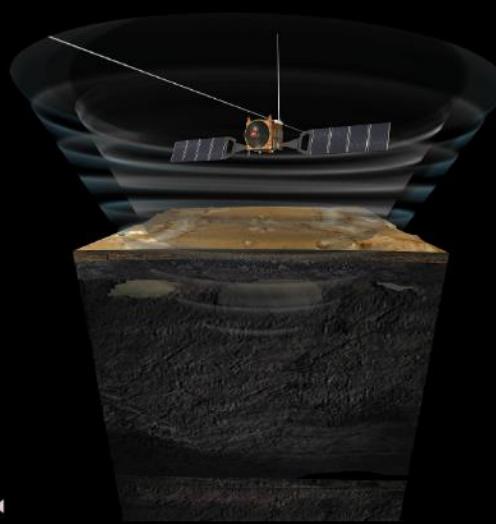
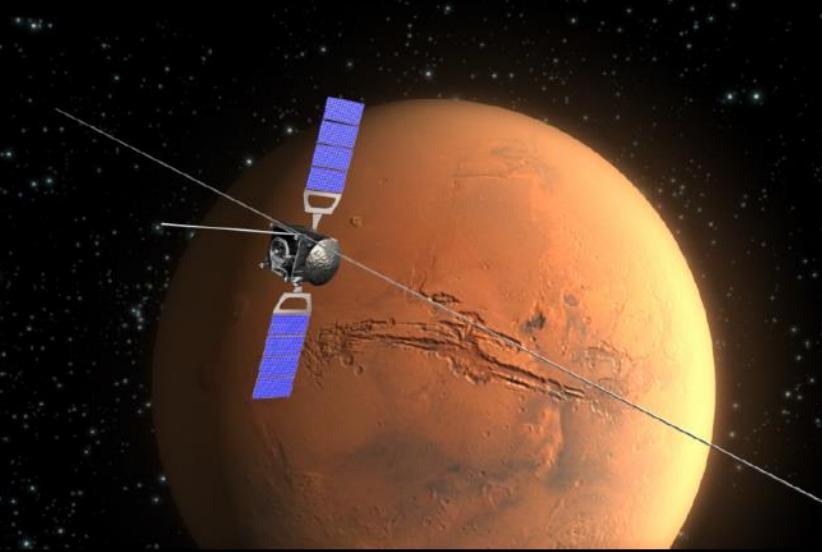
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The work reported here was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

MARSIS

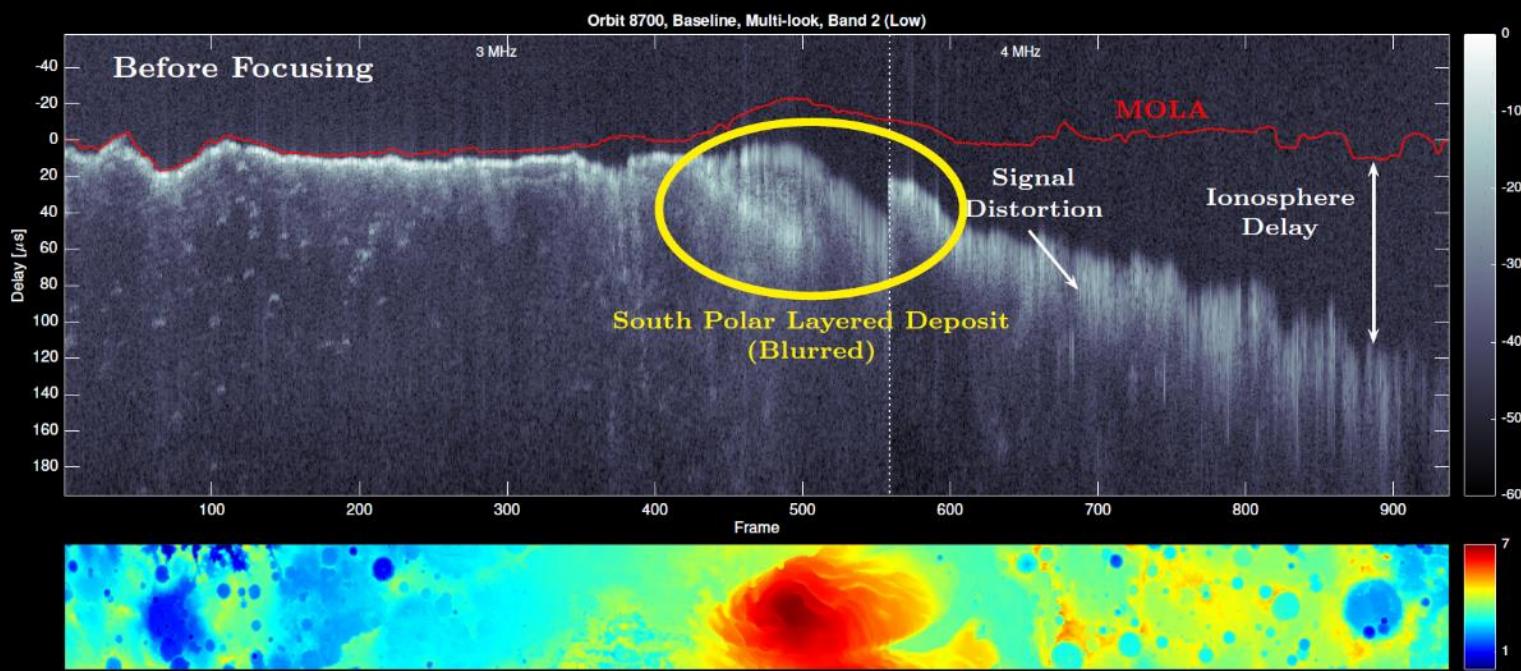
- Radar sounders employ low frequency RF transmissions at 1-20 MHz to penetrate ice deposits and reveal ice thickness, as well as internal layering
- MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) instrument aboard Mars Express has been collecting data since 2005
 - Over 12 years, MARSIS has accumulated over 7,200 radargrams in 16,000 orbits
 - Operates with 1 MHz bandwidth centered at 1.8, 3, 4, and 5 MHz
 - Free-space resolution 150 m (85 m in subsurface ice medium)
 - Beamforming performed onboard through unfocused Doppler processing
- Return signal is often heavily distorted and delayed by Mars' ionosphere, especially during Mars day time



Autofocus Algorithm

- Effort to develop efficient ionosphere autofocus algorithm for MARSIS
- Performs joint optimization of 3-coefficient ionosphere solution space
 - Not constrained to Chapman model with Gaussian electron density profile
 - Found that subspace of feasible solutions is quite small, dramatically improving speed
 - Implementation in C/C++ (called for multi-threading in Python)
- Novel focusing metric maximizes correlation with simulated radargram
- Automatic depth correction for refractive index of sub-surface ice

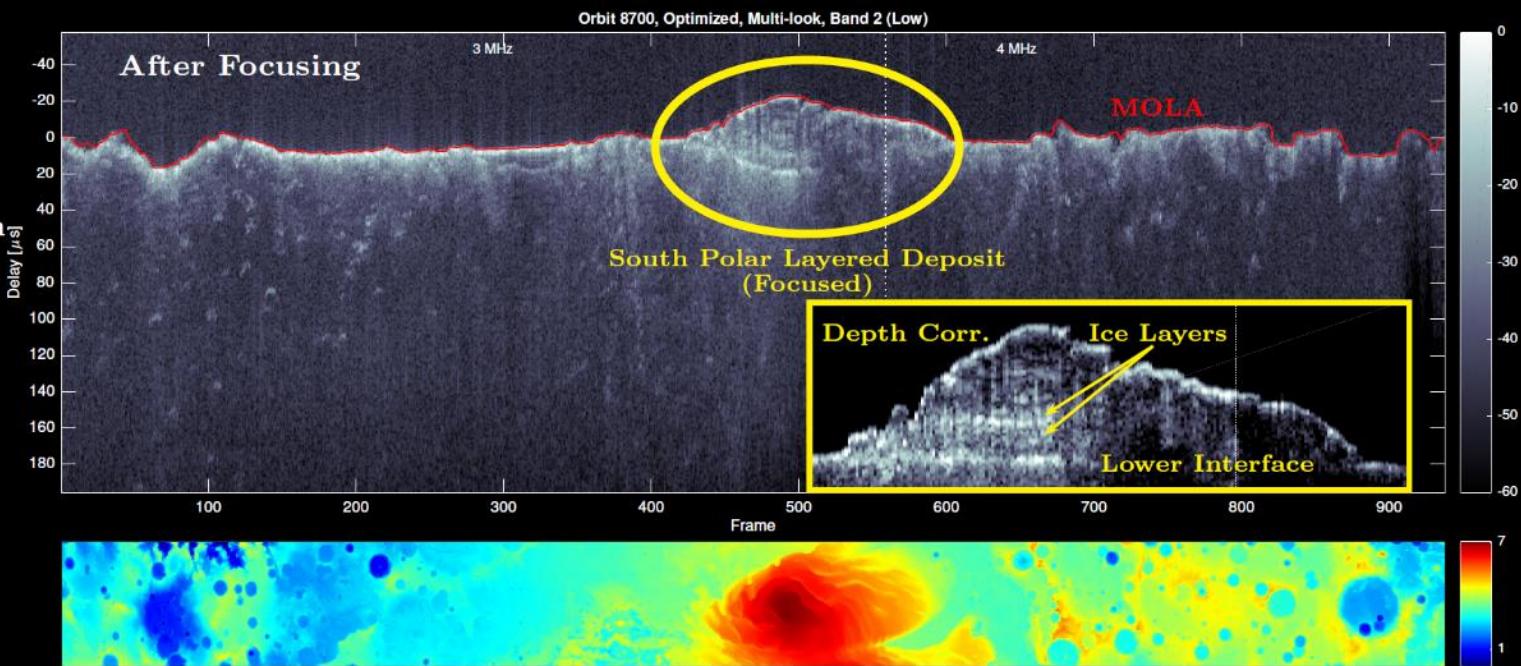
Baseline
No Correction
Orbit 8700
SPLD



Autofocus Algorithm

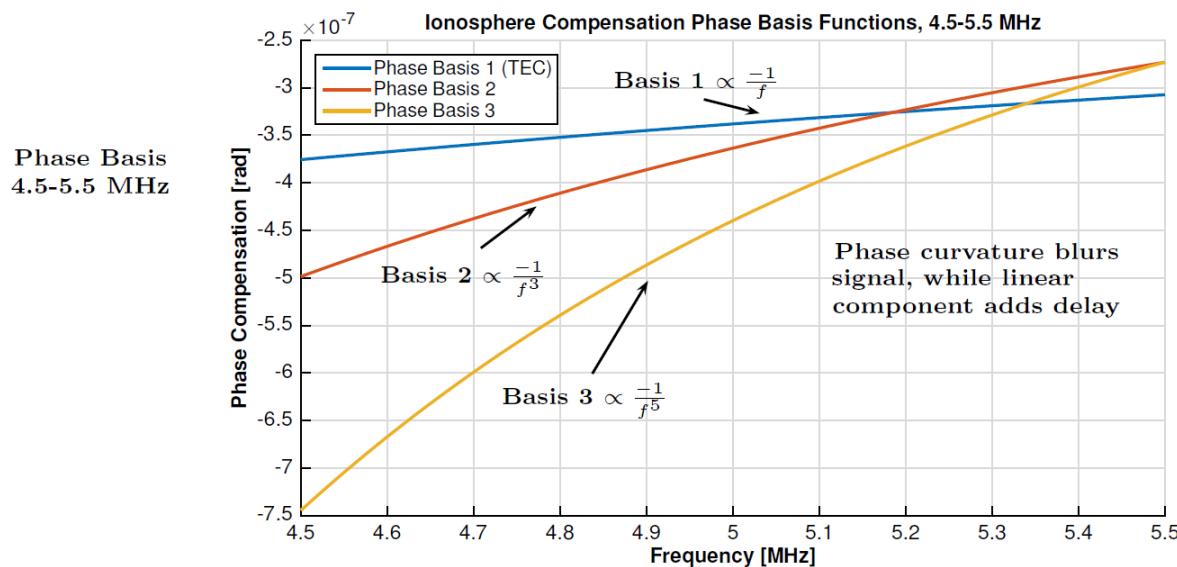
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Optimized
With Correction
Orbit 8700
SPLD



Ionospheric Signal Distortion Model

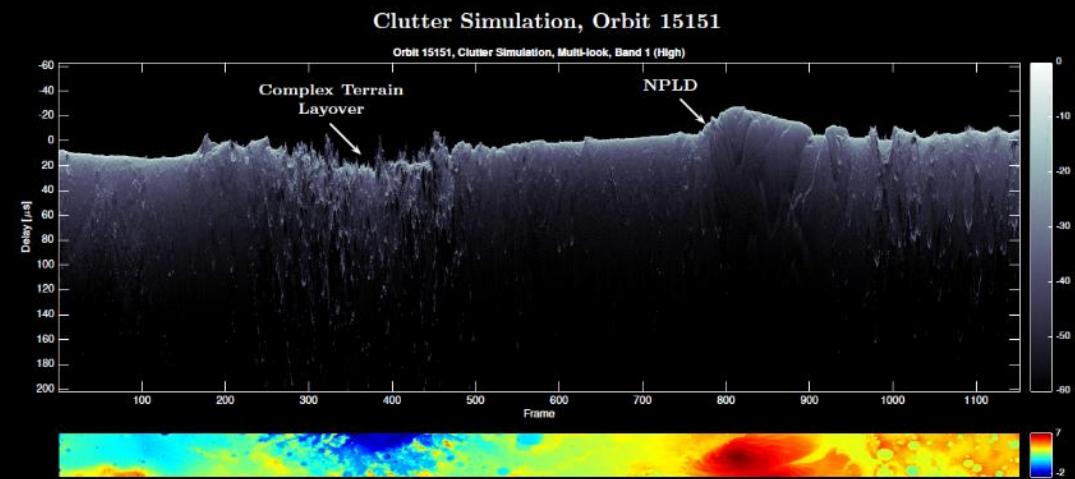
- MARSIS radar signals are delayed and distorted as they traverse the ionosphere
- Effect of signal propagation through plasma can be modeled as a linear combination of phase basis functions in frequency domain (*Safaeinili et al., 2007*)
 - Basis functions: $\phi(f) \propto \frac{1}{f}$, $\frac{1}{f^3}$, and $\frac{1}{f^5}$
 - Electron density profile: $N_e(z)$, Altitude: z



$$\phi(f_{MHz}) = \frac{-2\pi}{c} \left(\underbrace{\frac{8.98^2}{f_{MHz}} \int N_e(z) dz}_{TEC, \psi_1} + \underbrace{\frac{8.98^4}{3f_{MHz}^3} \int N_e^2(z) dz}_{\psi_2} + \underbrace{\frac{8.98^6}{8f_{MHz}^5} \int N_e^3(z) dz}_{\psi_3} \right)$$

Autofocus Score Metric

- Originally tried contrast metric (maximized peak value at nadir MOLA elevation)
 - Works well for smooth terrain, but can add artifacts for complex layover geometries
 - Focusing to a single elevation does not capture subtlety of layover near surface
 - Instead, implemented alternative focus metric: maximize correlation with simulated radargram based on MOLA
 - Optimize correlation for each frame independently
 - Requires realistic simulation for each orbit
 - Added penalty term to avoid focusing to sub-surface returns not in simulation
 - Developed C/C++ radar simulator to be run during autofocus process



Correlation term
(actual data vs. sim.)

$$\psi_{optim} = \operatorname{argmax}_{\psi} \frac{\sum_n |r(\psi, n)|^2 \cdot |s(\psi, n)|^2}{\left(\sum_{n, \text{before MOLA}} |r(\psi, n)|^2 \right)^\alpha}$$

Penalty term
(penalize focusing to sub-surface echoes)

ψ : iono. coefficients

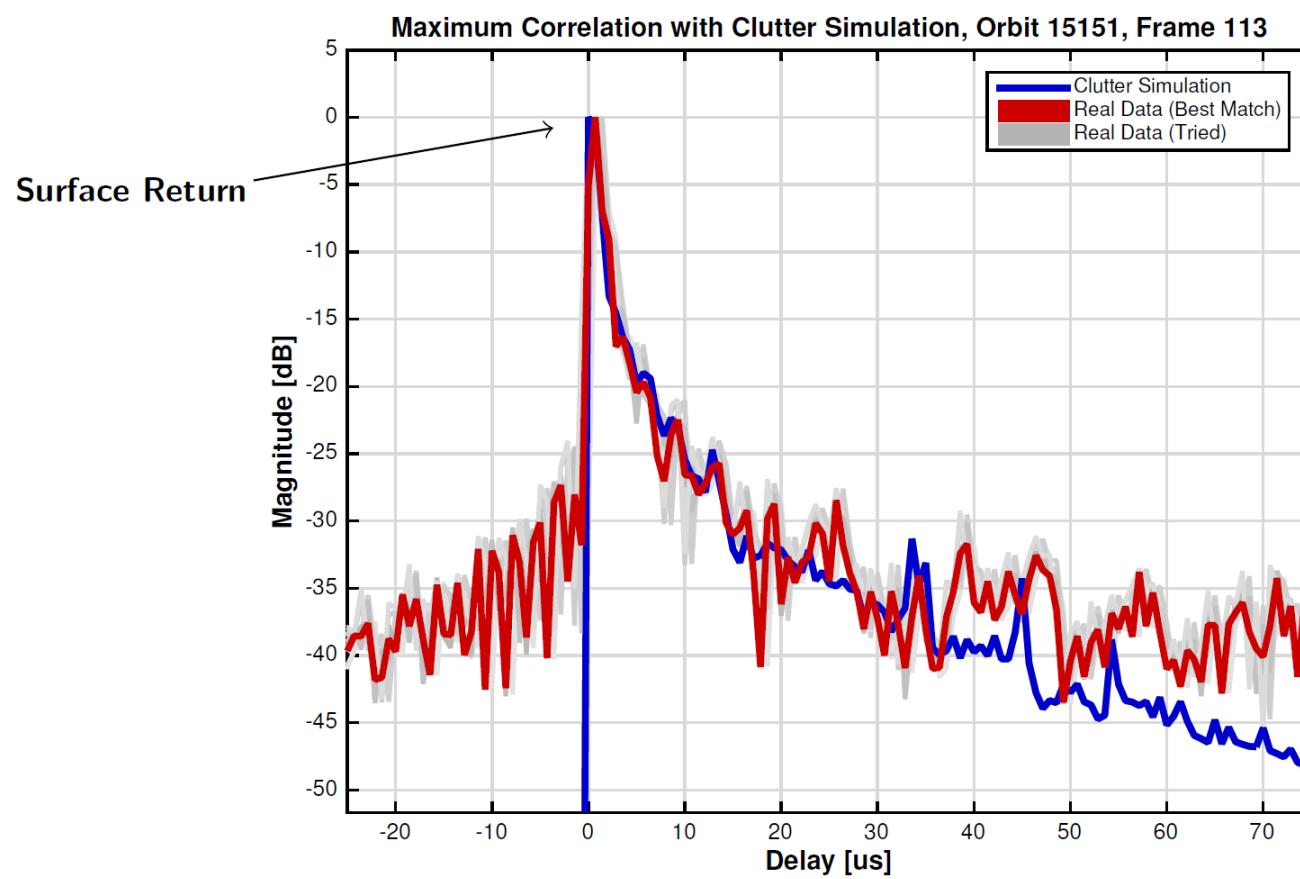
r: actual radargram after iono. corr.

s: simulated radargram
c: weighting factor

α : weighting factor

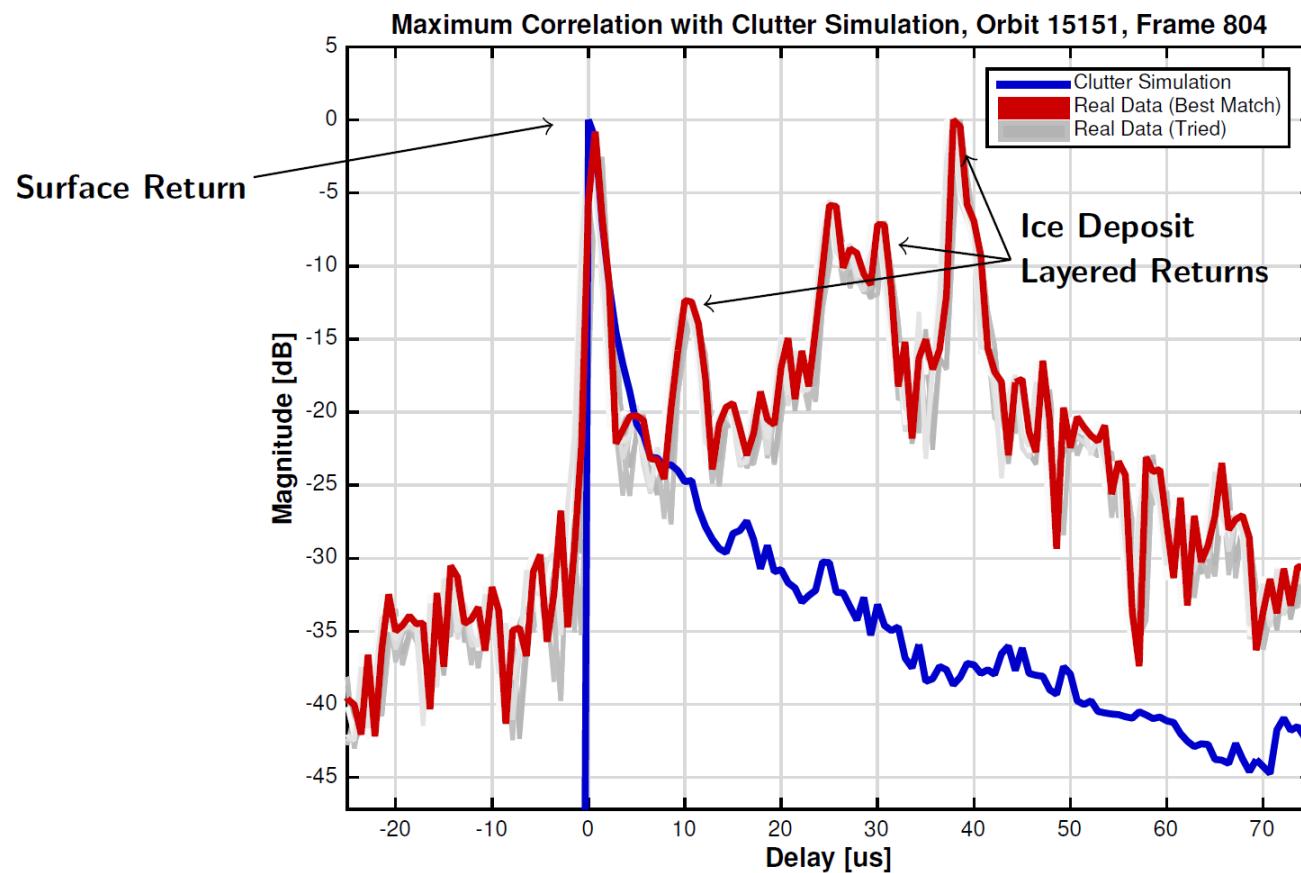
Example of Focus Metric (Specular Return)

- Orbit 15151, Frame 113: Echo dominated by single specular return
 - Simplest case: no layover or sub-surface returns
 - Maximum correlation when data is aligned with peak



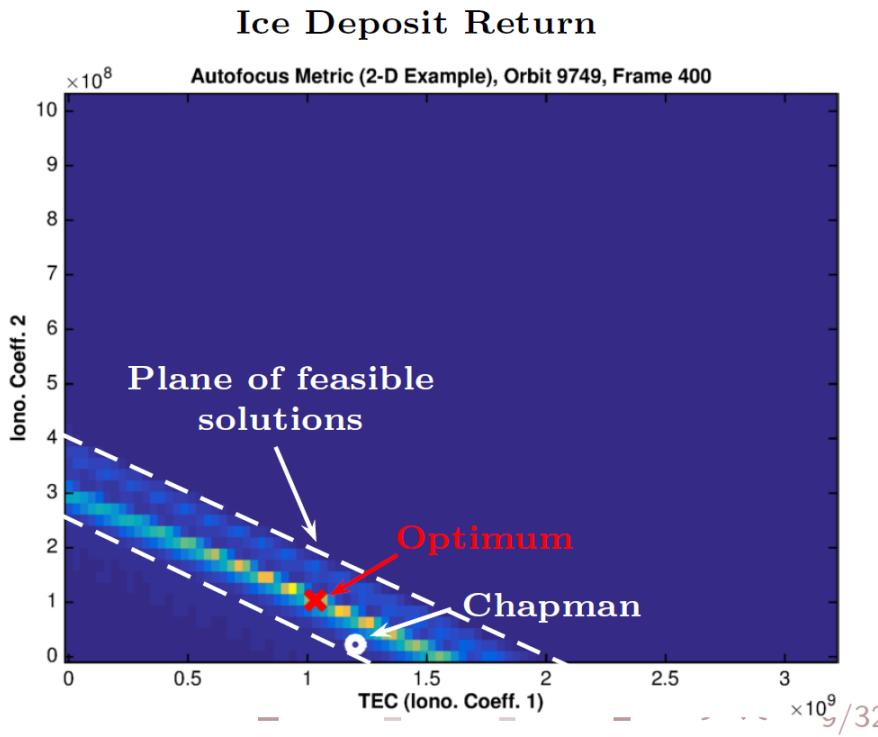
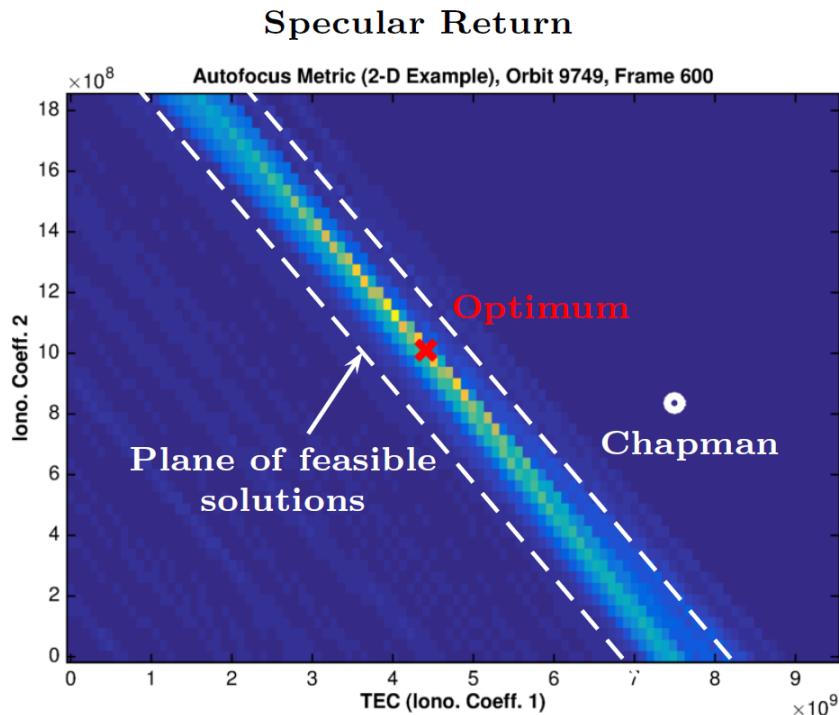
Example of Focus Metric (Ice Deposit)

- Orbit 15151, Frame 804: Sub-surface echo from ice boundary stronger than surface echo!
 - Difficult case: secondary reflection is not predicted in clutter simulation
 - Rely on penalty factor to avoid erroneously aligning second peak with surface



Feasible Solution Space

- Perform joint optimization of 3-dimensional coefficient space through grid sampling
 - Non-convex, so gradient descent approaches converge to sub-optimal local maxima
- Discovered that feasible solution space is much smaller than full coefficient space
 - Each individual coefficient has associated (negative) time delay
 - All three delays must add to fixed value to match MOLA (within tolerance)
 - Sampling only reasonable configurations yields significant speed increase



Approximate Delay of Ionospheric Coefficients

- Each moment of ionospheric model has associated (negative) time delay.
- Estimate associated delay from Fourier Transform identity.
- Use approximate delays to rule out TEC configurations that are not feasible.

$$\text{Time Delay } x(t - t_0) \iff e^{-j\omega t_0} X(j\omega)$$

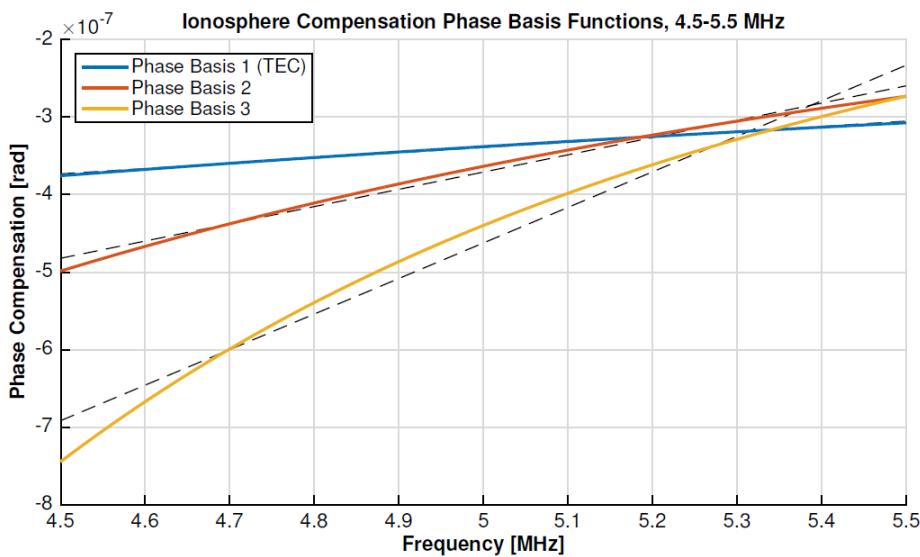
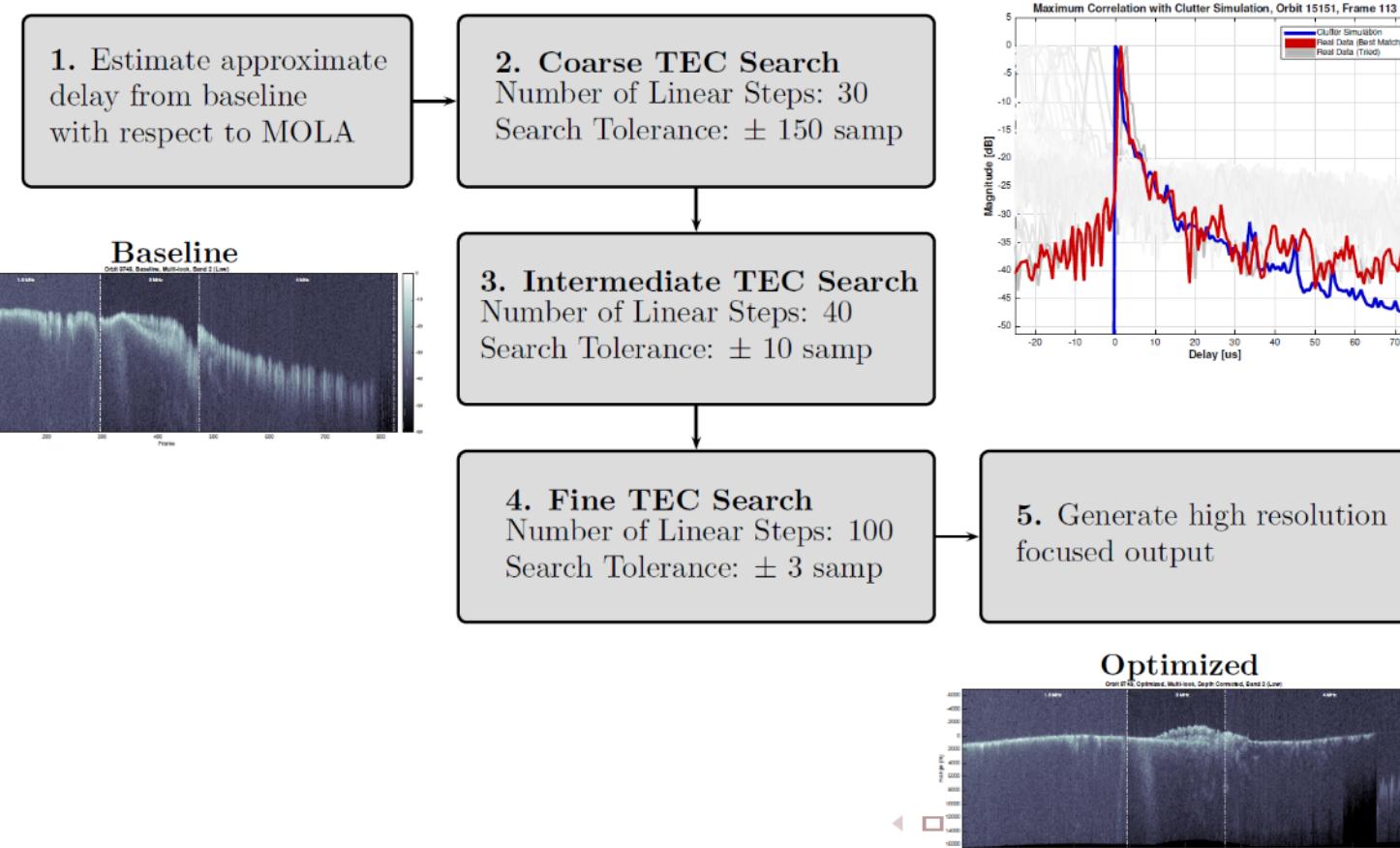


Table 1. Approximate time delays corresponding to ionospheric coefficients for each band frequency.

	ψ_1 Delay (samp/unit)	ψ_2 Delay (samp/unit)	ψ_3 Delay (samp/unit)
Band 1 (1.8 MHz)	-8.71e-8	-2.43e-6	-4.50e-5
Band 2 (3 MHz)	-3.04e-8	-2.83e-7	-1.69e-6
Band 3 (4 MHz)	-1.70e-8	-8.75e-8	-2.85e-7
Band 4 (5 MHz)	-1.08e-8	-3.54e-8	-7.30e-8

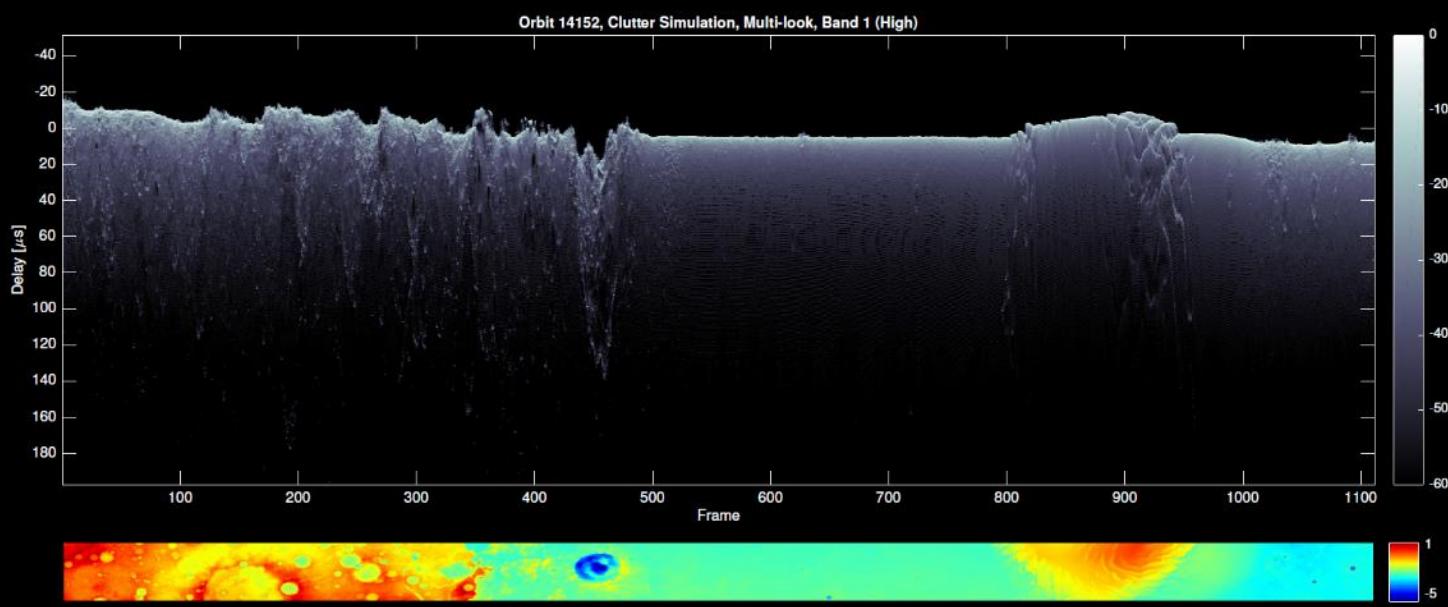
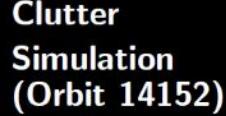
Successive Estimation of TEC Configuration

- Successively refine TEC estimate with 3 stages of varying resolution.
- Only search configurations with estimated delay within specified tolerance of MOLA.
- Delay tolerance decreases in each stage, as resolution increases.
- Verified that 99.9% of solutions are identical to full grid search, with 140x speed improvement.



Clutter Simulation Algorithm

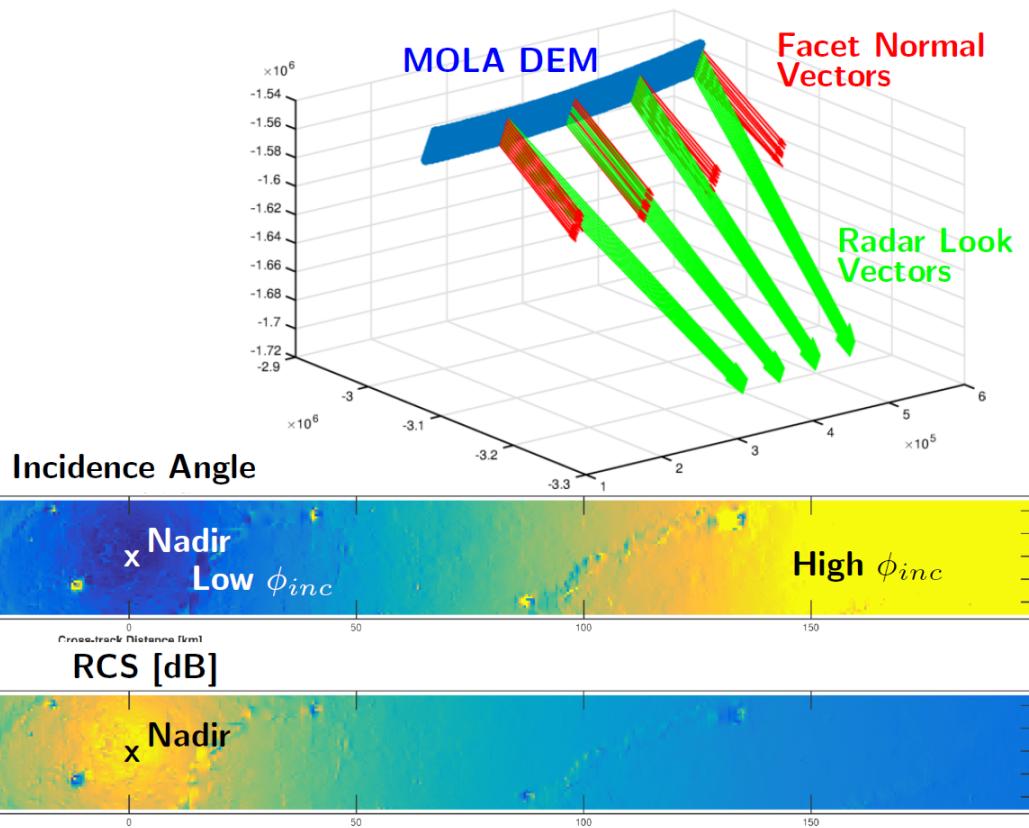
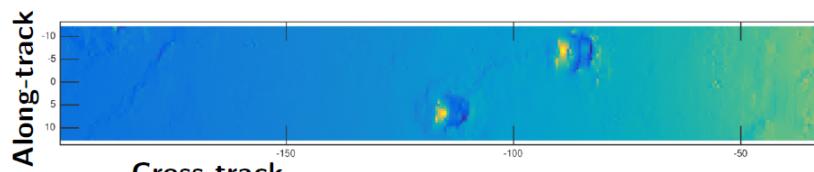
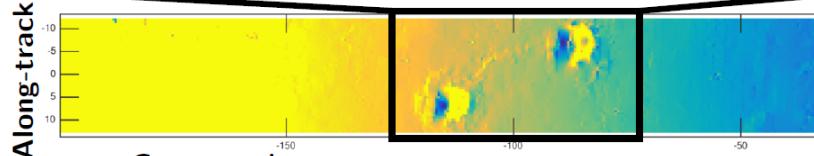
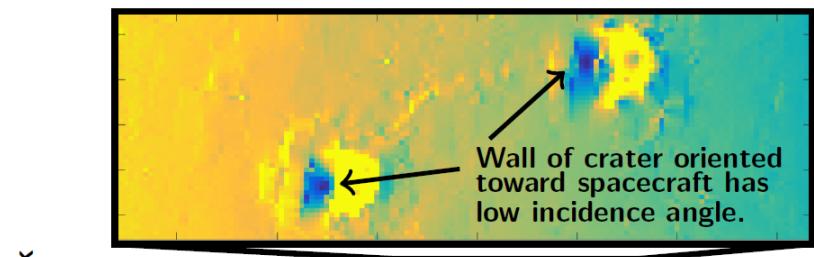
- Realistic clutter simulation necessary for use in maximum correlation metric.
 - For each spacecraft XYZ position:
 - 1 Extract MOLA DEM on surface grid (25 km along-track x 400 km cross-track)
 - 2 Compute Euclidean distance from spacecraft to each point on grid
 - 3 Use Hagfor's Scattering Model to compute expected $RCS(\phi_{inc})$ for each facet
 - Calculate normal vector of each facet of DEM (based on terrain slope)
 - Compute incidence angle to each facet, ϕ_{inc}
 - 4 Apply synthetic beam pattern (8 km along-track) and combine non-coherently



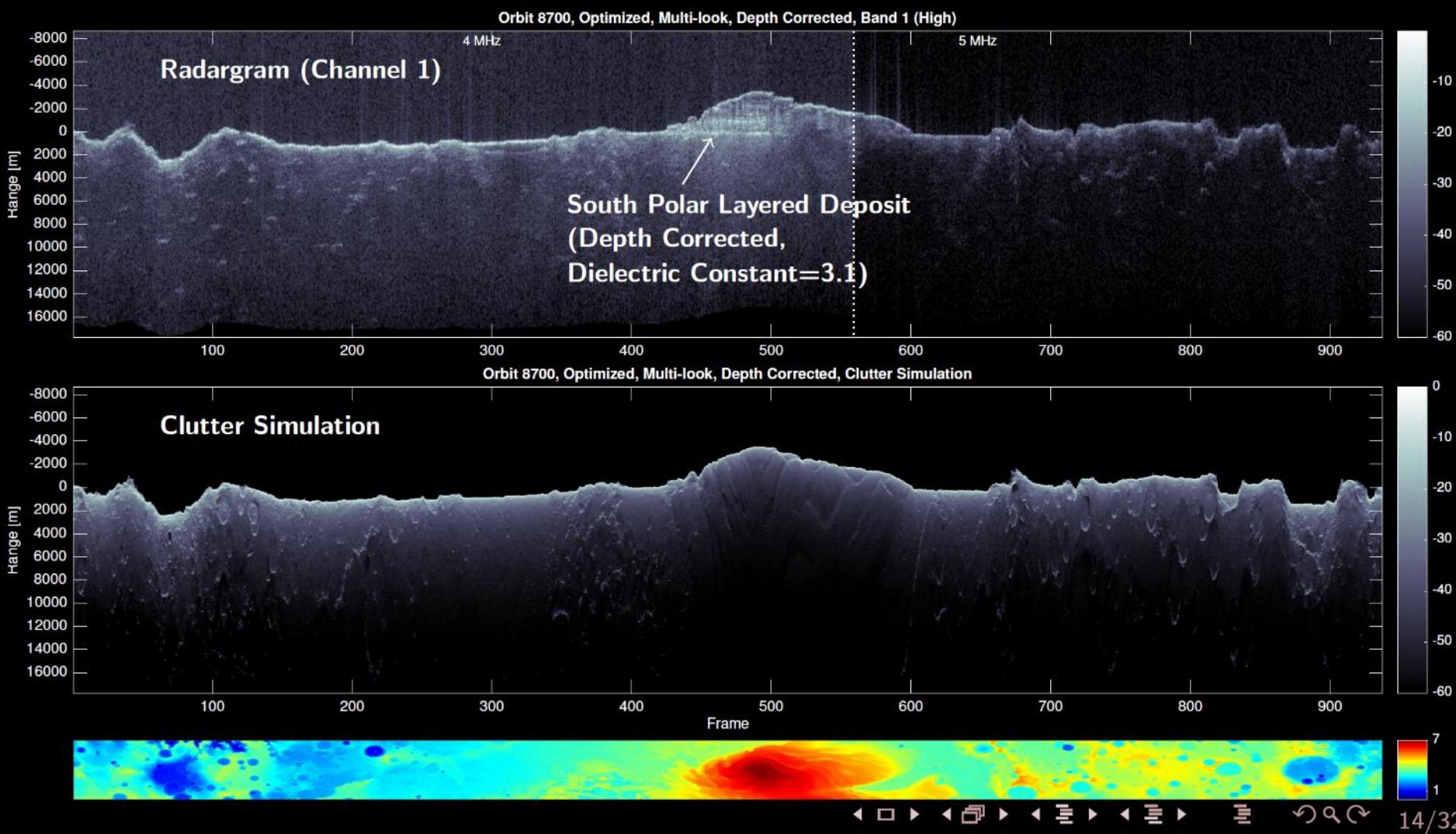
Hagfors' Scattering Model

- Scattering model based on Hagfors specular scattering [Campbell, 2011; Harmon, Campbell, and Ostro, 1982].
- Empirically tuned model parameters to match MARSIS radargrams (used value of C=6000; focus quality invariant to scaling factor on RCS for this purpose).
- For each DEM facet, compute RCS based on incidence angle $\sigma_0^{oc}(\phi_{inc})$.

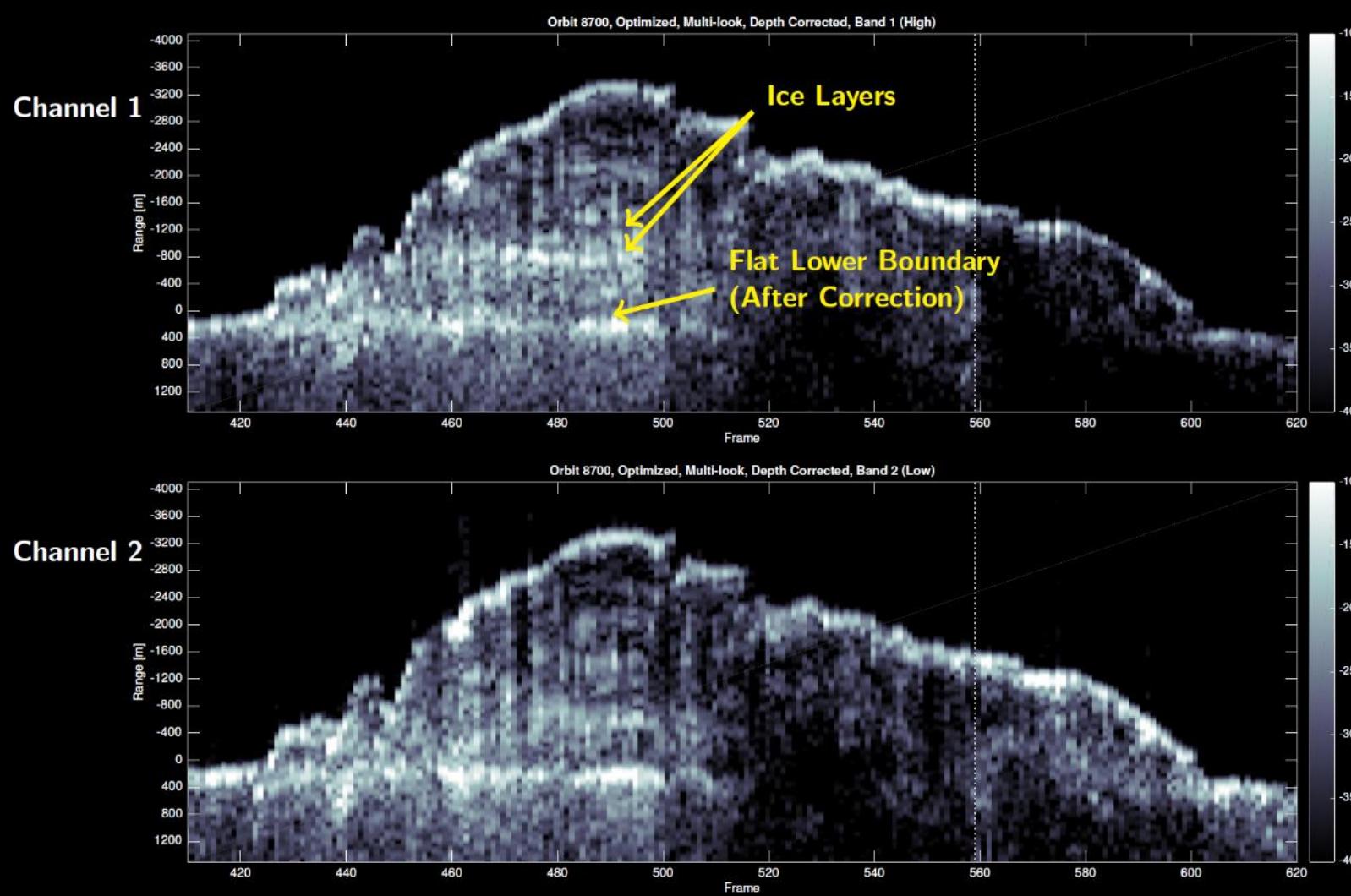
$$\sigma_0^{oc}(\phi_{inc}) = \overbrace{\frac{C\rho_0}{2} \left(\cos^4(\phi_{inc}) + C\sin^2(\phi_{inc}) \right)^{-3/2}}^{\text{Hagfors specular scattering}}$$



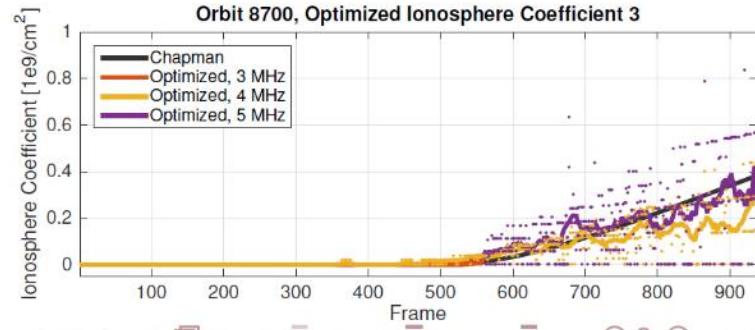
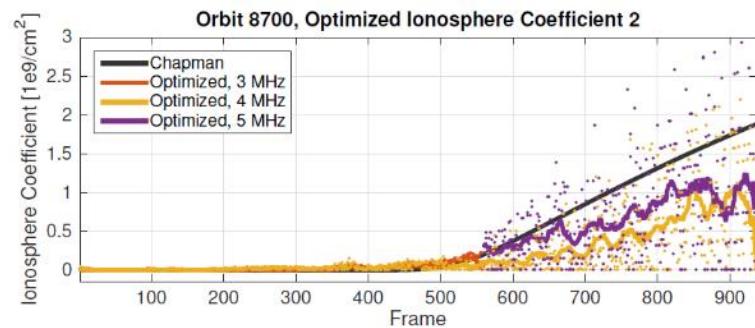
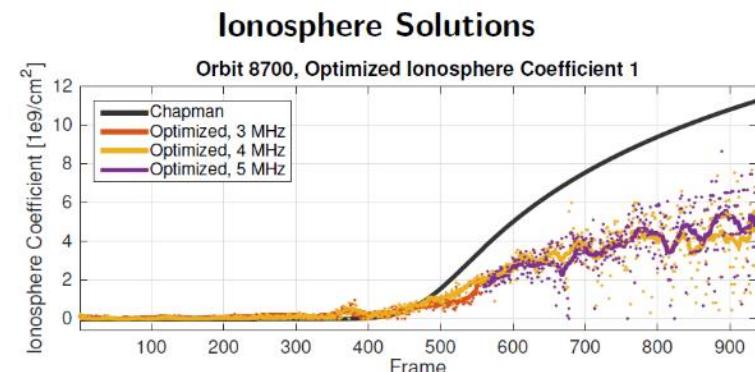
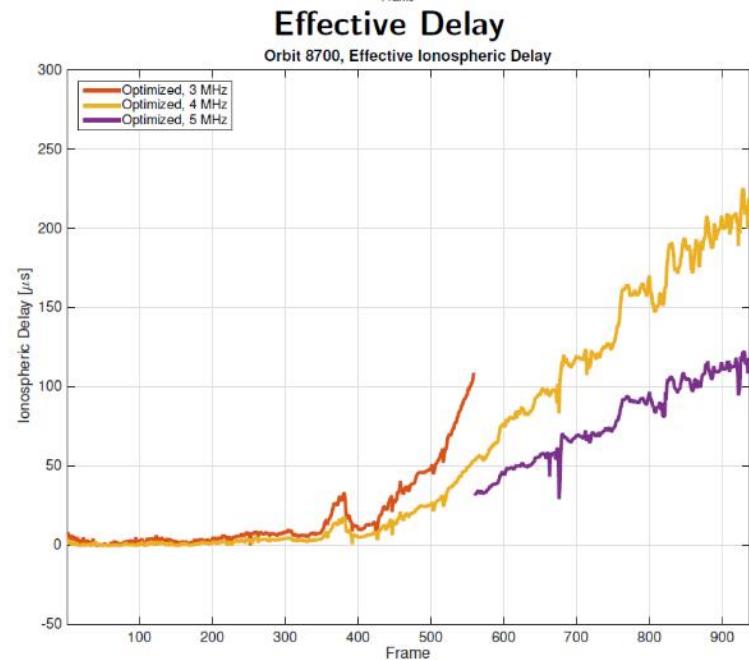
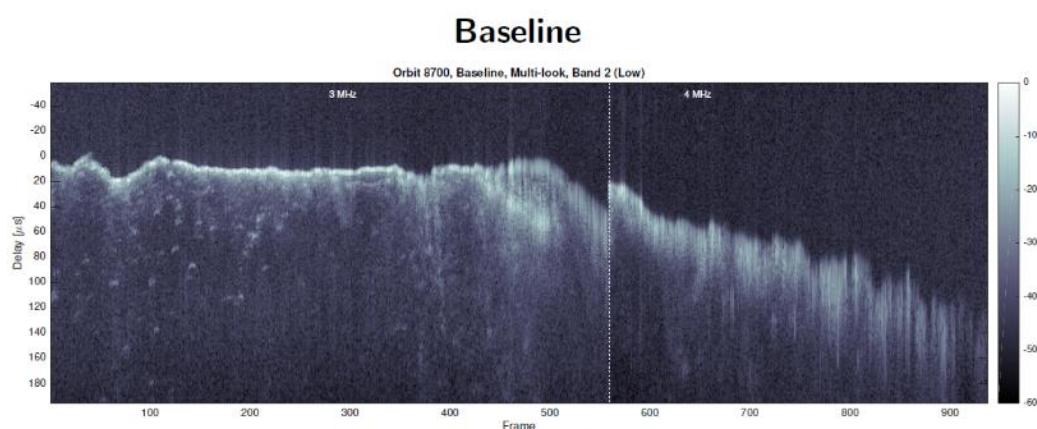
1. Focused Output (Orbit 8700, SPLD)



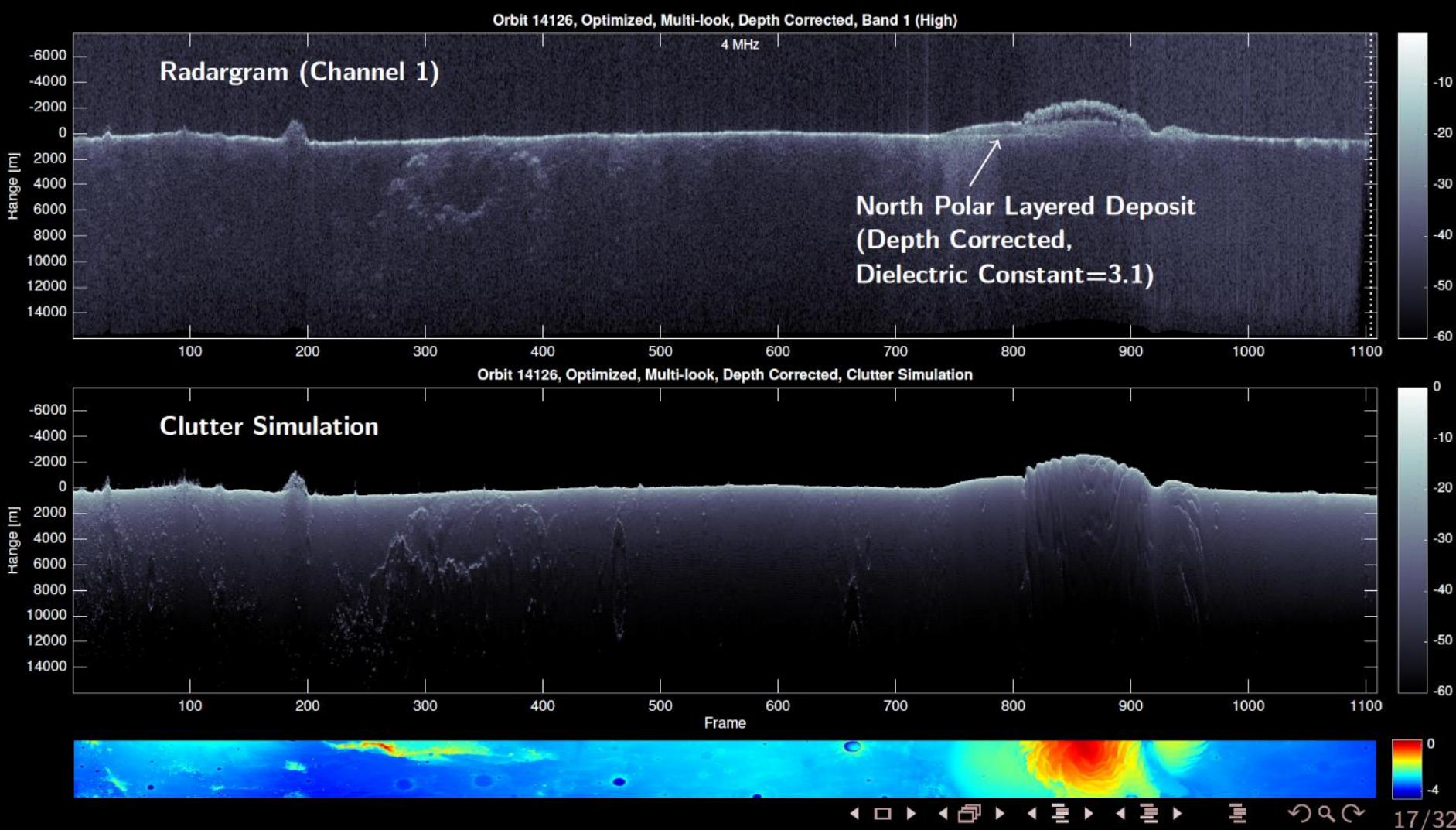
2. Ice Deposit Stratigraphy (Orbit 8700, SPLD)



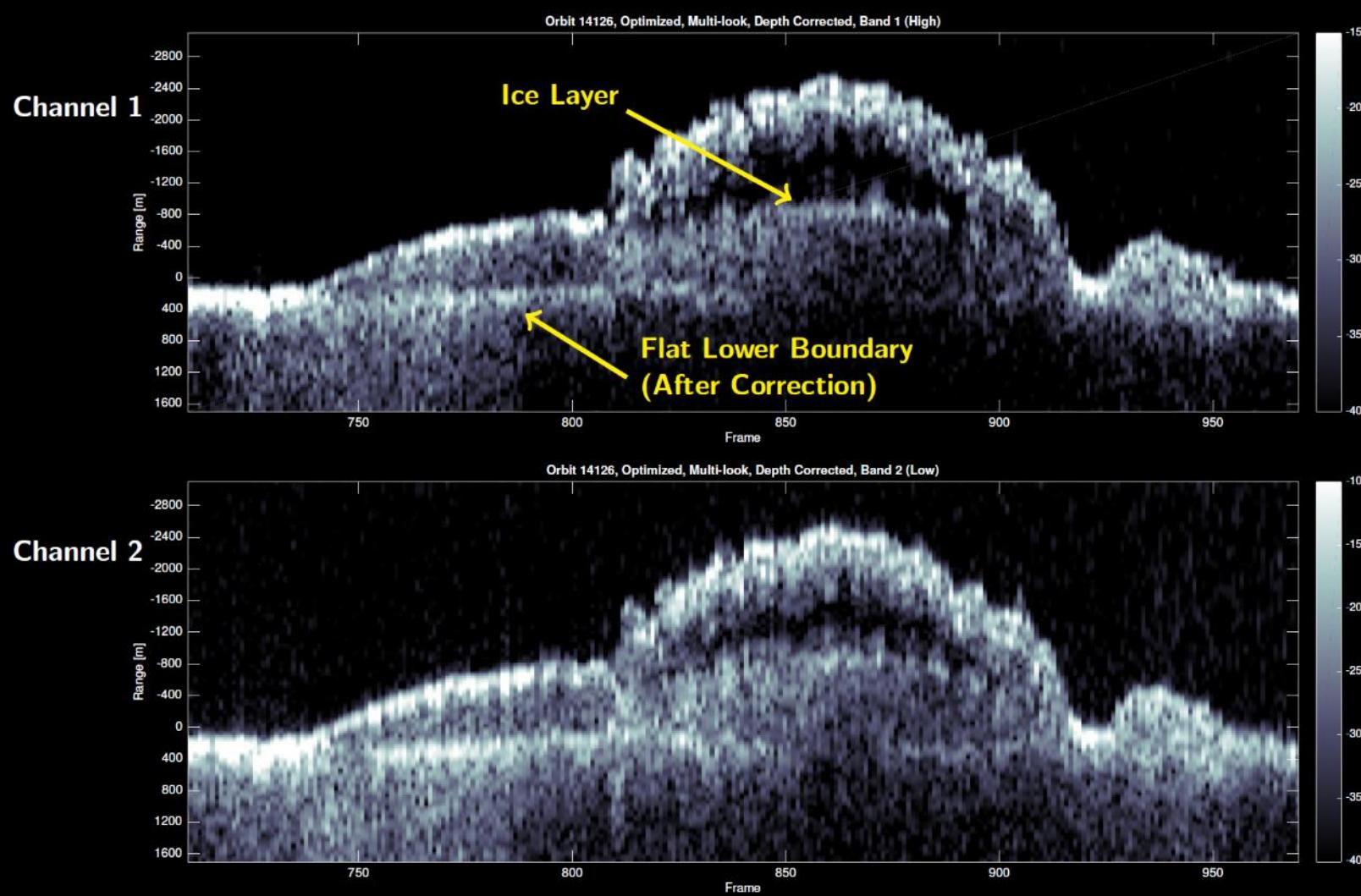
3. TEC Solutions (Orbit 8700, SPLD)



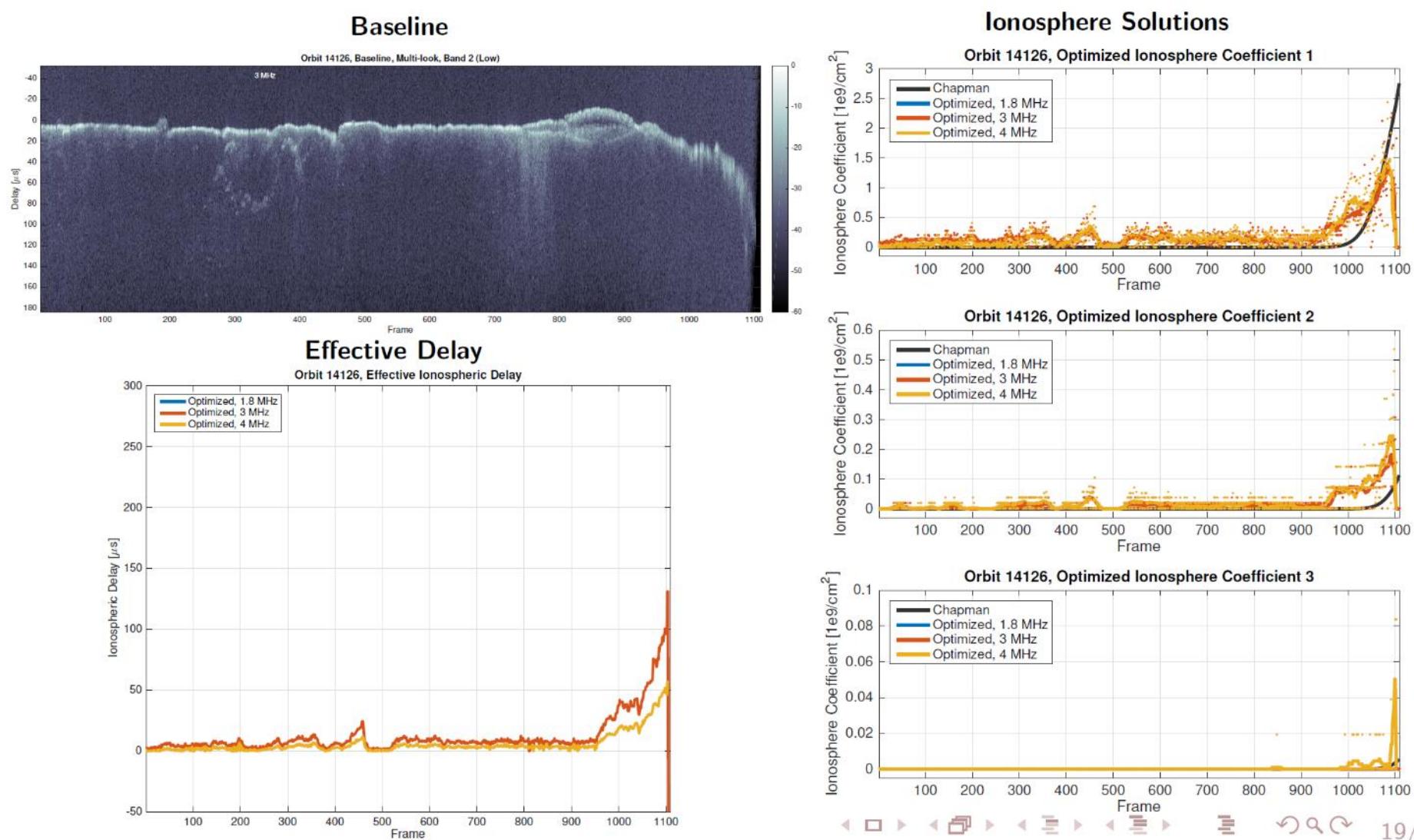
1. Focused Output (Orbit 14126, NPLD)



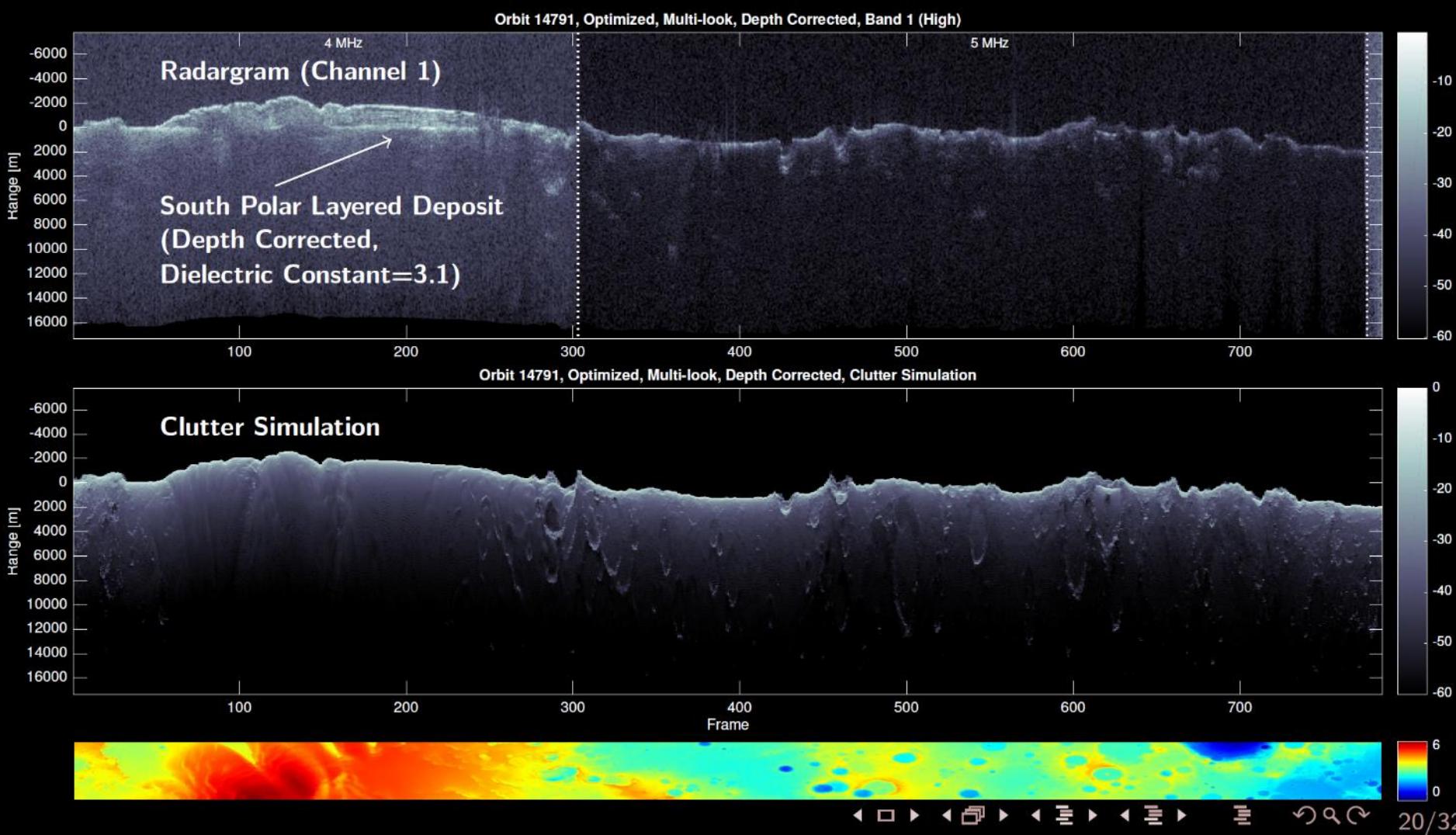
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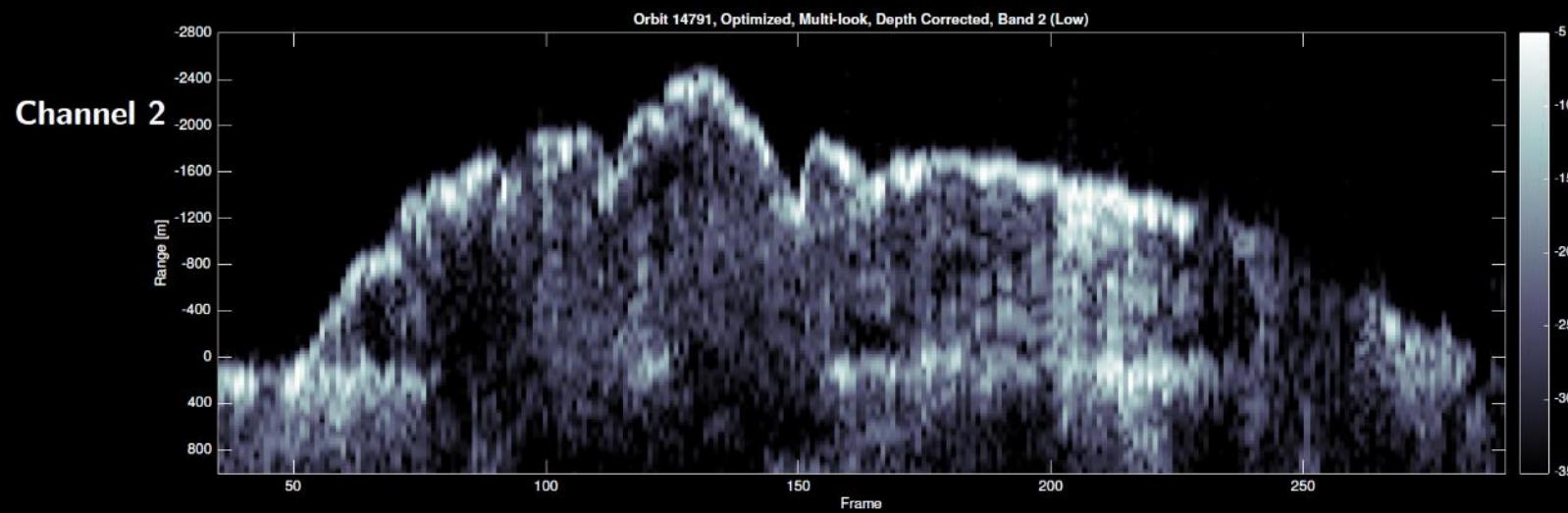
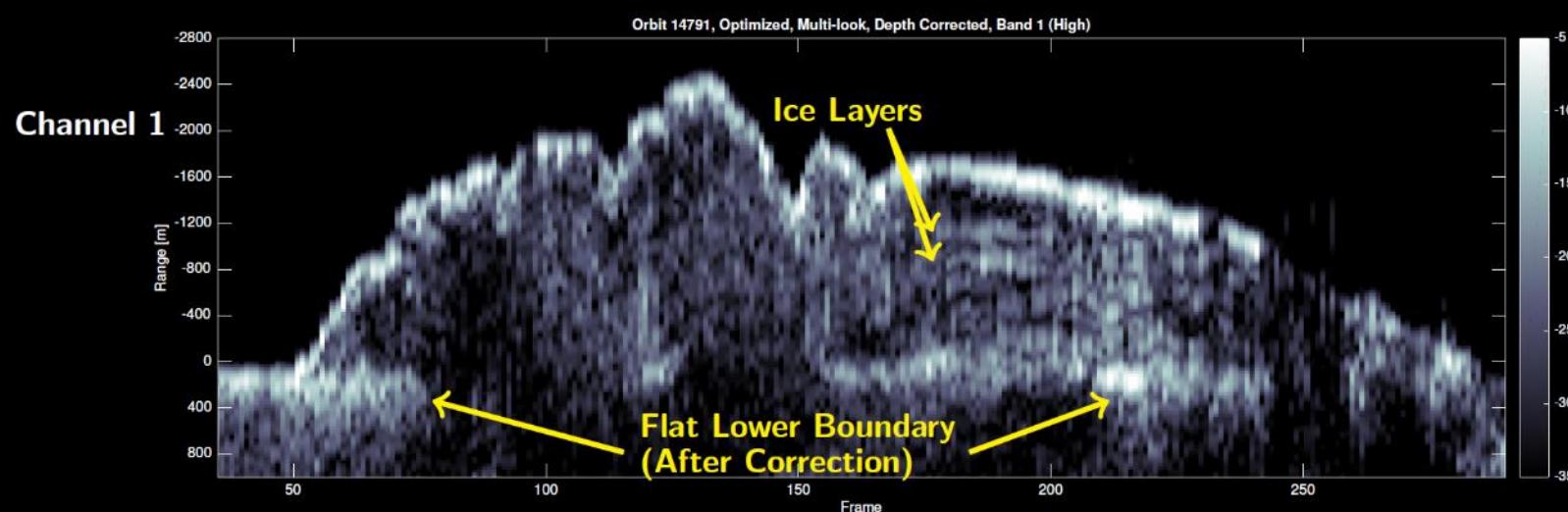
3. TEC Solutions (Orbit 14126, NPLD)



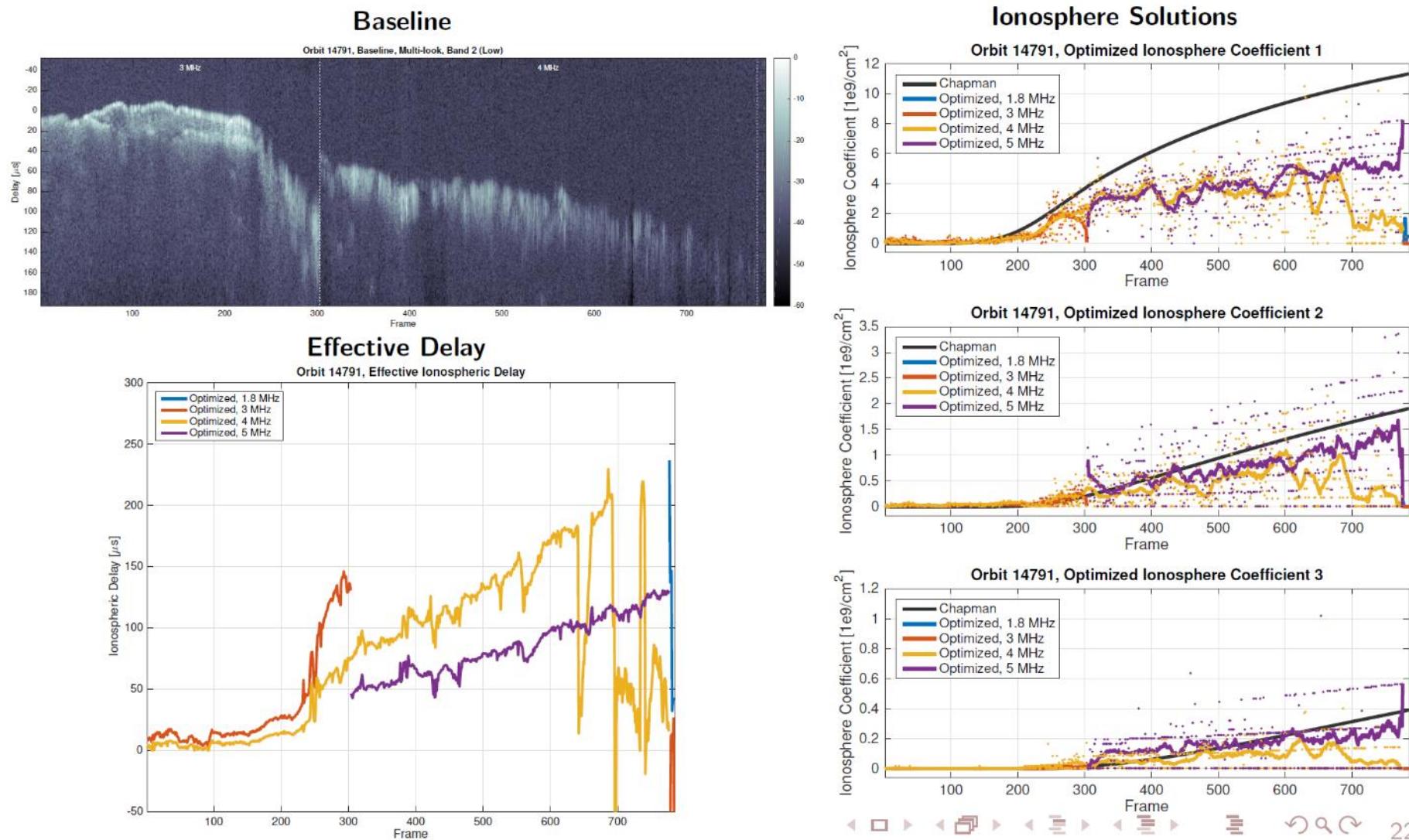
1. Focused Output (Orbit 14791, SPLD)



2. Ice Deposit Stratigraphy (Orbit 14791, SPLD)



3. TEC Solutions (Orbit 14791, SPLD)



Conclusion

- A radar autofocus algorithm aided by knowledge of Martian terrain has been developed for MARSIS that compensates for signal distortion of the Mars ionosphere
- An objective function has been formulated that focuses the radar response by maximizing correlation with a simulated radargram
- The MOLA digital elevation model with 500 m resolution was used to generate simulated radargrams based on the spacecraft trajectory
- The algorithm has been optimized to immediately “prune” unreasonable solutions that differ from the known surface bounce delay based on MOLA
- All 7000+ radargrams collected over 12 years have been re-focused with a parallelized C/C++ implementation of the algorithm